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Weldability of a Nickel-Based Superalloy

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Abstract

The electron beam welding process is used to investigate the weldability of the Ni-based superalloy Udimet 720LI. This is a modified form of the alloy Udimet 720, which has reduced concentrations of interstitial elements such as boron, silicon, and carbon. The history of high strength superalloys like this one suggests that welding will be difficult because of their tendency towards *hot cracking* during the welding process, or *strain-age* cracking during the post-weld aging process. Studies were done on several sizes of weldability test specimens to determine if Udimet 720LI will exhibit cracking tendencies. It was found that the alloy was not susceptible to hot cracking unless it had received the four-step aging heat treatment that is recommended by the manufacturer. It was also found that a restrained weldment is susceptible to strain-age cracking; however, if the weldment is allowed to deform then warpage can occur instead of cracking.

Introduction

This weldability study of Udimet 720LI (Ni-16.15wt%Cr-14.7Co-5.0Ti-2.5Al-3.0Mo-1.25W) was conducted in support of NASA - Lewis Research Center's Stirling component technology program. The goal of this program is the development of a Stirling power converter capable of generating 12.5 kWe/cylinder while operating at 25% efficiency (Ref. 1). The discussion that follows will describe some of the Stirling space power converter (SSPC) requirements and a brief background on the welding of superalloys.

The SSPC uses a heat pipe to capture the sun's heat. The power and efficiency requirements dictate that the heat pipe will need to operate at a hot-end temperature of 1050 K (777°C) and a temperature ratio (hot end/cold end) of 2.0. The lifetime durability requirement is 60,000 hours (Ref. 1). These demanding time and temperature requirements can only be met by a few alloys. The Ni-based superalloy Udimet 720LI was determined to be the best candidate for the heat pipe application because of its high creep strength and corrosion resistance at high temperatures.

Since fabrication of the SSPC requires welding, the issue of developing successful welding procedures must be addressed. The contractor building the SSPC hoped to be able to develop electron beam welding (EBW) procedures, and supplied some of the welded specimens that were examined in this investigation. The EBW process was chosen because it produces a weld cross-section with a high depth-to-width ratio, which means that full penetration welds in thick sections could be made in a single pass and with minimal heat input.

Previous welding studies involving Ni-based superalloys have shown that alloys such as Udimet 720LI, which have relatively high concentrations of the alloying elements aluminum and titanium, can be difficult to fusion weld because of their tendency to crack during welding or during the post-weld aging process (Refs. 2, 3). Since Udimet 720LI falls in this category of "unweldable" superalloys, it was expected that cracking problems would be encountered during the fabrication process.

Two types of cracking can develop when welding the high strength Ni-based superalloys: *hot cracking* occurs during the welding process while the metal is solidifying, and *strain-age cracking* occurs during the post-weld aging heat treatment.

As a weld travels, the base metal at the front of the weld pool is heated past its melting point, creating thermal expansion and compressive stresses in the base metal ahead of the weld pool. Simultaneously, the rear of the weld pool is solidifying and contracting, thus creating tensile stresses in the base metal and the solidified weld metal. If this tensile stress exceeds the yield stress of the material in an area where the ductility is insufficient, cracking can occur (Ref. 2). This type of cracking, which occurs during the welding process, is called solidification cracking, or hot cracking.

Hot cracking is more likely to occur in materials that have high concentrations of low melting interstitial elements such as silicon and boron. These elements tend to be rejected by the advancing solid/liquid interface. This results in an increased concentration of interstitial elements ahead of the interface, which can cause the formation of low melting phases that wet the grain boundaries in the last areas to solidify (such as the weld centerline). These areas are thus weakened and are more susceptible to cracking (Ref. 2). Since Udimet 720LI is manufactured with a low interstitial (LI) element composition, it was hoped that hot cracking would not be a problem.

If a superalloy is successfully welded with no hot cracking problems, it usually must be heat treated to restore properties and relieve residual stresses. During heat treatment, the material is strengthened by the precipitation of $Ni_3(Al,Ti)$, which is known as the γ' phase. This precipitation can also be initiated during welding in the unmelted heat affected zone (HAZ) adjacent to the weld metal. The temperature gradient that forms in the HAZ during welding causes the γ' microstructure to be nonhomogeneous, which results in variations in strength. If residual stresses resulting from the welding process exceed the fracture stress at some location in the material during the aging process, then strain-age cracking is likely to occur (Ref. 3).

It is empirically accepted that superalloys having a total Al and Ti content of greater than 6 atomic percent will precipitate a larger volume of γ' and will therefore be more difficult to weld due to a tendency toward strain-age cracking (Ref. 3). Udimet 720LI has a total Al and Ti content of greater than 11 atomic percent; thus, there was concern about the development of successful fusion welding procedures. The SSPC fabrication contractor reported that one company had determined that Udimet 720LI was less likely to crack if it was subjected to a proprietary pre-weld solution annealing heat treatment. This heat treatment was reported to dissolve the γ' in the base metal, leaving it in a more weldable condition. This proprietary heat treatment was used on several selected specimens prior to welding.

In summary, it was hoped that the low interstitial element concentration of Udimet 720LI would make it possible to successfully weld without exhibiting hot cracking. It was also anticipated that a pre-weld heat treatment would leave the microstructure in a condition more amenable to welding and aging without cracking. Thus, the purpose of this investigation was to determine if cracking is a problem when fusion welding Udimet 720LI, and if this material could therefore be used in the fabrication of the SSPC.

Procedure

Materials

Material was purchased in bar form from Special Metals Corporation (SMC) in 4.7, 5.8, 10.2, and 16.5 cm diameters. These bars were in wrought form, except for the 5.8 cm diameter bar, which was formed by hot isostatic pressing (HIP) of powder metal. The composition of the various heats of Udimet 720LI, as reported by SMC in weight percent, is listed in Appendix A.

Circle Patch Test Specimen

The circle patch test is designed to restrain the welded specimen during the welding process, thus creating residual stresses in both the solidified weld metal and the base metal. An alloy's weldability can thus be determined by observing whether it can withstand these residual stresses without cracking.

It should be noted that the amount of restraint provided by a specimen is not quantifiable, and it is not always easy to determine which specimen design induces more stress in a weldment. However, if the test specimen is not strong enough, deformation can occur. This would relieve the residual stresses resulting from the welding process and reduce the risk of cracking. Thus, circle patch specimens (Refs. 3,5) were used in four different sizes, which are shown schematically in Fig. 1. The smaller specimens were intended to provide the highest restraint, since they have no reduced section and thus have the greatest thickness at the weld.

All specimens were cut using the electro-discharge machining (EDM) process, and subsequently ground to remove the recast layer that results from this process. The reduced sections on circle patch specimens were turned on a lathe.

Welding Procedures

Unless otherwise specified, all welds were made using a Model W2 Hamilton Standard electron beam welding machine. Slight variations in beam current were obtained, as noted below, and are due to the stepping motor controller that is used on this machine. There is no continuously adjustable control; thus, all other parameters can cause small fluctuations in the beam current.

Eleven 4.7 cm diameter specimens were processed to determine the step in the weld/heat treatment procedure most likely to cause cracking. This was accomplished by removing one or more specimens after each step of processing and examining them for cracking. Nine of the eleven specimens were subjected to the pre-weld solution anneal, and two were welded without the pre-weld heat treatment. Full penetration electron beam (EB) welds were made in all specimens using the following parameters:

100 kV; 12.4 mA; 76.2 cm/min.

Two specimens were cut from the 5.8 cm diameter powder metallurgy bar and were welded without the pre-weld solution anneal because the steel HIP can would not have survived. The HIP can was left on to provide additional restraint. The following EBW parameters were used:

100 kV; 12.4 mA; 76.2 cm/min.

Four 10.2 cm diameter specimens were welded with different parameters after receiving the pre-weld solution heat treatment. The intent was simply to vary heat input and welding speed to test their affects on weldability. The following EBW parameters were used:

1. 100 kV; 5 mA; 58.0 cm/min.

2. 80 kV; 6 mA; 76.2 cm/min. (Partial penetration).

3. 100 kV; 7.5 mA; 76.2 cm/min.

4. 100 kV; 7.0 mA; 76.2 cm/min. (This specimen was aged prior to welding, to simulate a repair weld).

Two 16.5 cm diameter specimens were welded in the as-received condition. The following EBW parameters were used:

100 kV; 7.1 mA; 76.2 cm/min.

Two additional 16.5 cm diameter specimens were welded after receiving the pre-weld solution anneal. The following EBW parameters were used:

100 kV; 7.5 mA; 76.2 cm/min.

Welded pieces produced by the SSPC fabrication contractor were also provided for this study. Their process involved 11.4 cm diameter cast-wrought Udimet 720LI bar that had the center machined out to produce an 11.4 cm diameter pipe with a wall thickness of 0.95 cm. After receiving the pre-weld solution anneal, the specimens had backing rings press fit into the ends that were to be welded. The specimens were then welded and the backing ring and the face of the weld were subsequently machined off in an attempt to relieve residual stresses in the weldment. They were then subjected to the four-step "CR" aging heat treatment, which is defined in the following section. Finally, they were cut into sections, and two of these were sent to NASA - Lewis for evaluation.

Post-weld Heat Treatment

After welding, uncracked specimens were subjected to a four-step heat treatment that produces the maximum creep strength in this alloy, as specified by SMC. This SMC "CR" heat treatment consists of the following four steps:

1. 1170°C for 4 hours; air cool. (This first step is a solution heat treatment. Heat up was made as rapidly as possible in an attempt to pass through the temperature range in which γ' precipitation is initiated. In this way, solutioning would occur before precipitation strengthening could cause cracking.)

2. 1080°C for 4 hours; air cool.

3. 845°C for 24 hours; air cool.

4. 760°C for 16 hours; air cool.

Examination Methods

The presence of cracking was determined using visual and metallographic inspection techniques on all specimens. Since non-destructive evaluation (NDE) would be necessary to assure the integrity of the final product, it was necessary to determine which NDE methods, if any, could be successfully applied to Udimet 720LI weldments. Specimens provided by the fabrication contractor were subjected to x-ray analysis, ultrasonic testing, and computer tomography.

Results

The metallographic examination of the 4.7, 5.8, and 10.2 cm diameter specimens will be discussed first, because they supplied the most conclusive data. Fig. 2 shows how the circular welds were sectioned to obtain transverse and tangential views of the weld metal.

No cracking was found on the surface of any of the eleven 4.7 cm diameter specimens after welding. After the first step of the CR heat treatment, however, nine of the eleven specimens were severely cracked. Fig. 3 is typical of the cracked specimens, with a crack running down the centerline of the weld and extending into the base metal.

The two specimens that did not exhibit surface cracking had received the pre-weld anneal. These two specimens appeared to survive all four steps of the CR heat treatment; no cracks were found on the surface when examined by optical microscopy. However, transverse sections revealed cracking in one of the specimens. The cracking ran through about 40% of the thickness of the specimen, but was not open to either surface (Fig. 4). Furthermore, both of the tangential sections revealed similar sub-surface cracking (Fig. 5).

This sub-surface cracking is by nature hazardous because it was not revealed by visual inspection techniques and was not always found in transverse weld sections. Tangential weld sectioning was the only reliable method of finding these cracks in circular welds.

The two 5.8 cm diameter powder metallurgy specimens were examined by optical microscopy after each step of the weld/heat treatment process. There was no cracking observed on the surfaces. Metallographic examination, however, revealed the same sub-surface cracking that was formed in the 4.7 cm diameter specimens.

After welding, the two 10.2 cm diameter specimens which had the lowest heat input showed no signs of cracking by optical or dye-penetrant inspection. After the first step of the CR heat treatment, the specimens were again examined optically and no cracking was found. It was initially believed that if the specimens survived the first step of the CR heat treatment, then residual stresses would be relieved and strain-age cracking would no longer be a concern. They were therefore examined only after the last three steps of the CR heat treatment were complete. Severe cracking was evident at this time in both specimens (Fig. 6).

Examination of the third 10.2 cm diameter specimen, which had the highest heat input, revealed small transverse cracks on the face of the weld after the first step of the CR heat treatment (Fig. 7).

Immediately after welding, cracking was observed in the weld and HAZ of the fourth 10.2 cm diameter specimen, which had received the four-step CR heat treatment prior to welding (Fig. 8). This specimen represented a repair weld that might be necessary during or after the fabrication process.

Metallographic examination of the 16.5 cm diameter specimens showed that no cracking was present after the weld/heat treatment process was completed. During the four-step CR heat treatment, however, these specimens warped to the shape of a saddle (Fig. 9). No warpage occurred in the 4.7, 5.8, and 10.2 cm diameter specimens. The lack of cracking in the larger specimens indicates that the warpage may relieve the stresses that would cause cracking in more highly restrained weldments.

Non-destructive examination (NDE) of the welds provided by the SSPC contractor was inconclusive. Wet and dry contact ultrasonic examination was unsuccessful due to the attenuation caused by the large grain size and thickness of the material. Computer tomography showed no indications of cracks or flaws of any kind. X-ray analysis revealed slight indications in two of the pieces, but the indications were not distinct enough to draw any definite conclusions.

Longitudinal weld sectioning of these pieces was then performed, revealing severe sub-surface cracking (Fig. 10). These cracks resembled those found in the 4.7 and 5.8 cm diameter specimens and is especially alarming because it was not revealed by any of the NDE methods that were attempted.

Discussion

The results of these tests confirmed that Udimet 720LI is not susceptible to hot cracking, unless the material has received the CR aging heat treatment prior to welding. However, Udimet 720LI was subject to strain-age cracking in restrained weldments, since all of the restrained specimens developed surface or sub-surface cracking after the welding and CR heat treatment processes.

The welding of Udimet 720LI results in residual stresses that are relieved in one of two ways during aging: deformation or strain-age cracking. All of the specimens tested exhibited one of these two defects either after welding or during the 'CR' aging heat treatment. The tests used in this study demonstrated that a higher degree of restraint was provided by the smaller diameter, thicker specimens.

A proprietary pre-weld solution annealing heat treatment was used to try to eliminate strain-age cracking, but was unsuccessful. Rapid heating during the first step of the four-step aging heat treatment was also tried as a means of avoiding cracking caused by precipitation hardening, but this had no apparent effect on the occurrence of strain-age cracking.

A single attempt to simulate a repair by welding a fully aged specimen was unsuccessful due to cracking during welding. This is a problem since it is likely that some sort of repair would be necessary during or after the fabrication process.

Based on the results of this study, it is concluded that welding of Udimet 720LI during the fabrication of the Stirling engine would be a risky endeavor, since strain-age cracking is very likely to occur. This cracking may actually go undetected unless destructive examination of the engine was performed, and obviously this is not an option.

Conclusions

1. The use of Udimet 720LI is not recommended for the heat pipe application of the Stirling engine because strain-age cracking is very likely to occur during some part of the welding process.

2. Udimet 720LI does not exhibit hot cracking during partial or full penetration electron beam welding unless it is in the aged condition.

3. Electron beam welded Udimet 720LI assemblies will either deform or crack during the 'CR' aging heat treatment, depending on the amount of restraint that is built in to the weldment.

4. The use of the proprietary pre-weld solution annealing heat treatment had no apparent affect on the weldability of Udimet 720LI.

References

1. L.G. Thieme and D.M. Swee, *Summary of the NASA Lewis Component Technology Program for Stirling Power Converters*, NASA Technical Memorandum 105640, October 1992.

2. K. Easterling, *Introduction to the Physical Metallurgy of Welding*, Butterworths & Co. Publishers, London, 1983.

3. M. Prager and C.S. Shira, *Welding of Precipitation-Hardening Nickel-Base Alloys*, Welding Research Council Bulletin 128, February 1968.

4. F.E. Sczerzenie, et al, *Udimet Alloy 720*, Report No. TR-88-002, Special Metals Corporation, May 1988.

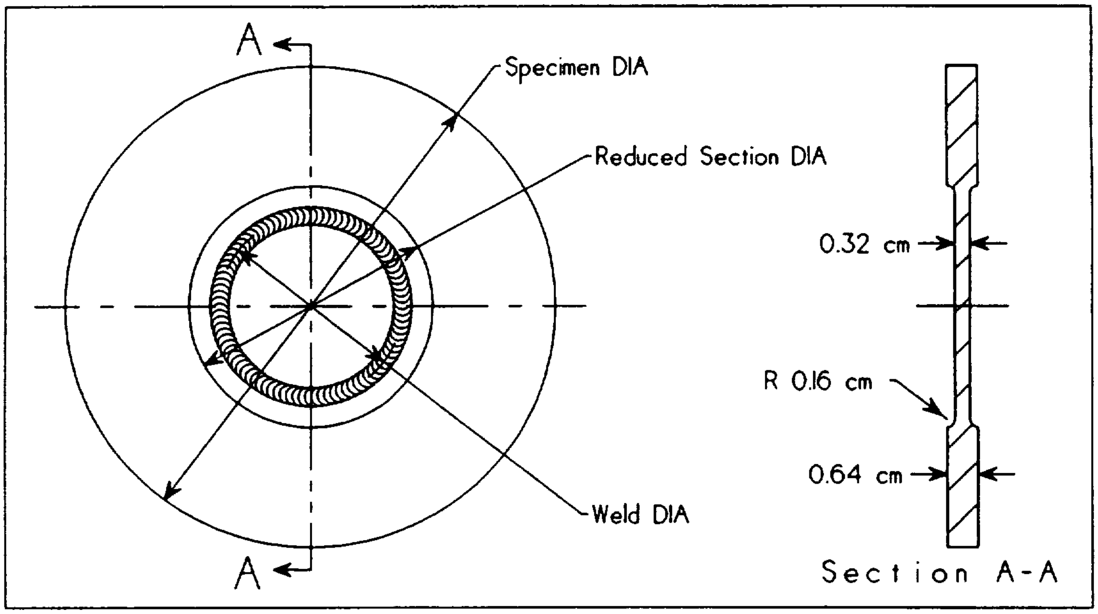
5. J.J. Vagi, et al, *Weldment Evaluation Methods*, Report No. 244, Defense Metals Information Center, August 1968.

Appendix A:

Composition of Udimet 720LI by Special Metals Corp. Heat Number

All quantities are weight percents.

Material	4.7 cm Dia. Bar	10.2 cm Dia. Bar	16.5 cm Dia. Bar	5.8 cm Dia. PM Bar
Heat No.	9-14431	89251	9-14120	BN91029
Ni	56.52	Bal.	Bal.	Bal.
Cr	16.58	15.90	16.12	16.41
Co	14.87	14.66	14.64	14.62
Ti	5.07	5.08	5.06	4.93
Al	2.52	2.70	2.63	2.52
Mo	3.02	3.03	3.03	3.00
W	1.21	1.24	1.18	1.25
C	0.011	0.010	0.010	0.008
B	0.0151	0.0154	0.0137	0.015
Zr	0.032	0.029	0.031	0.03
Mn	0.01	0.01	0.01	<0.01
Cu	0.01	0.03	0.01	<0.01
P	0.002	0.002	0.002	<0.01
Si	0.01	0.01	0.01	0.01
Fe	0.08	0.07	0.09	0.04
S	0.0003	0.0011	0.0002	0.003
Mg	10 PPM		29 PPM	
O_2				103 PPM
N_2				1 PPM
Cb				<0.01
Ta				<0.01
V				<0.01
Hf				<0.02



Specimen Diameter	Reduced Section Dia.	Weld Dia.	Thickness at Weld
4.7 cm	none	2.5 cm	.64 cm
5.8 cm	none	2.5 cm	.64 cm
10.2 cm	5.0 cm	3.7 cm	.32 cm
16.5 cm	11.4 cm	8.9 cm	.32 cm

Fig. 1. Circle Patch Test Specimen Dimensions (refs. 2, 3).

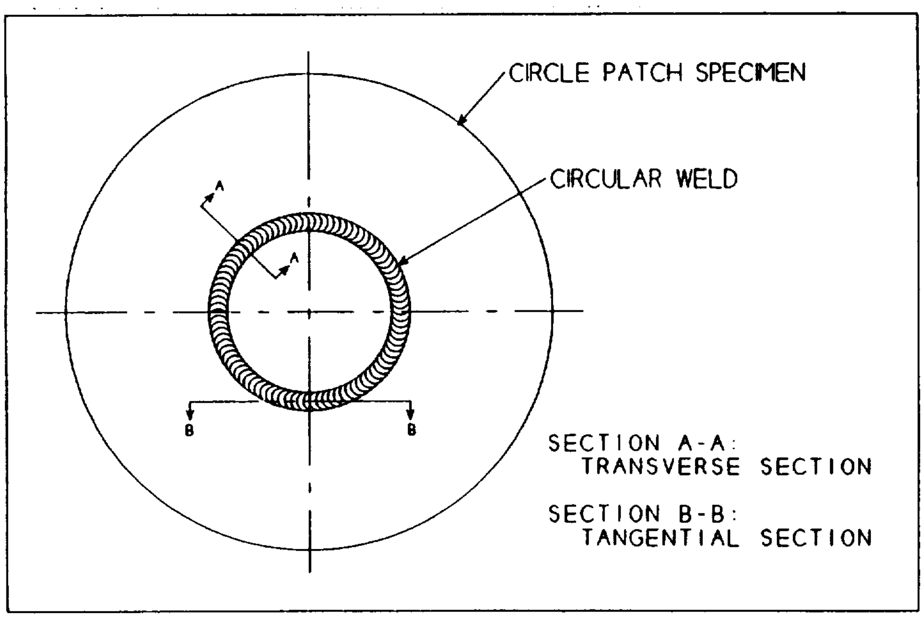


Fig. 2. Circular Weld Sectioning Techniques

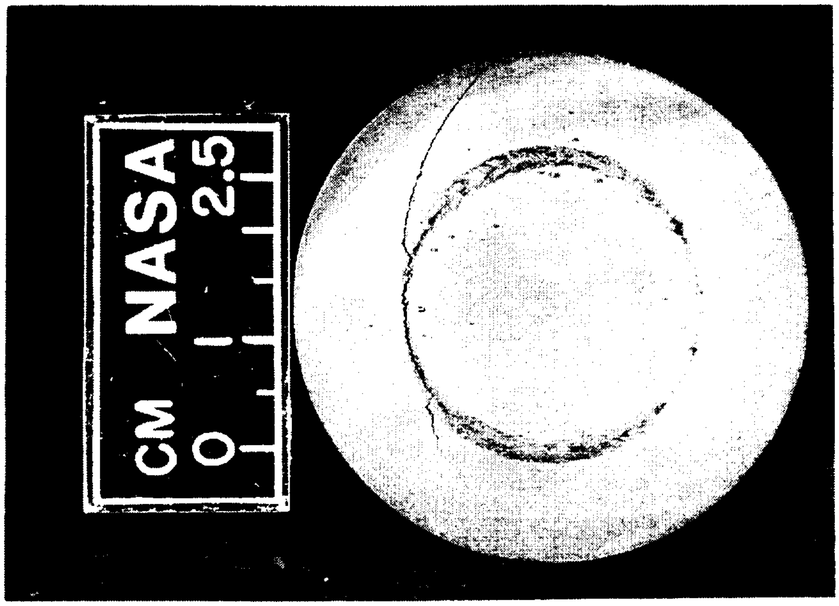


Fig. 3. Strain-age Cracking in 4.7 cm Diameter Specimen.

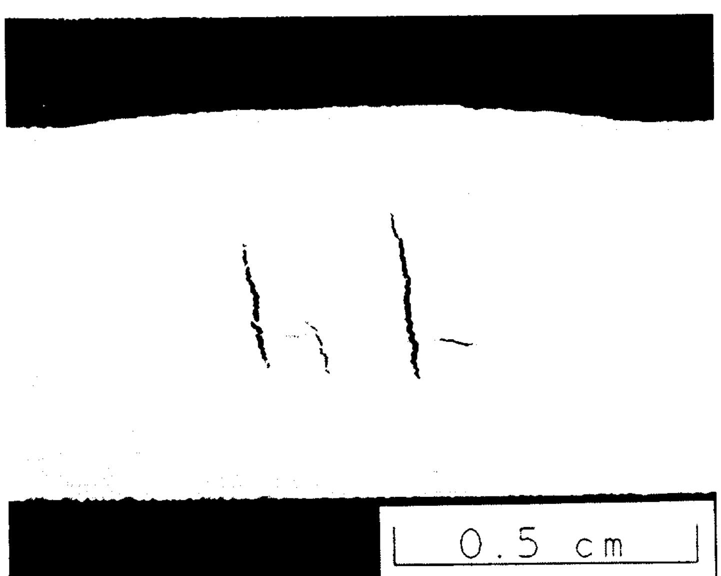


Fig. 4. Sub-surface Cracking in a Transverse Weld Section - 4.7 cm Diameter Specimen

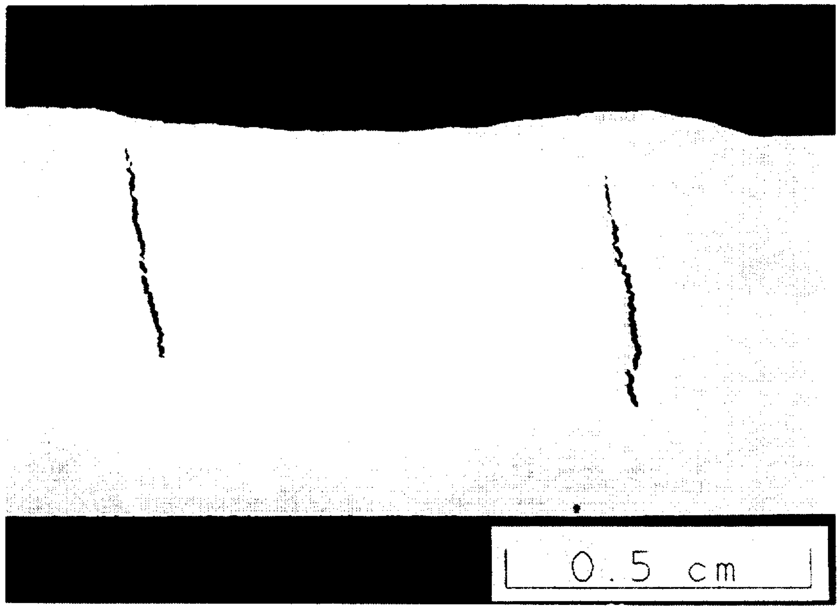


Fig. 5. Sub-surface Cracking in a Tangential Weld Section - 4.7 cm Diameter Specimen

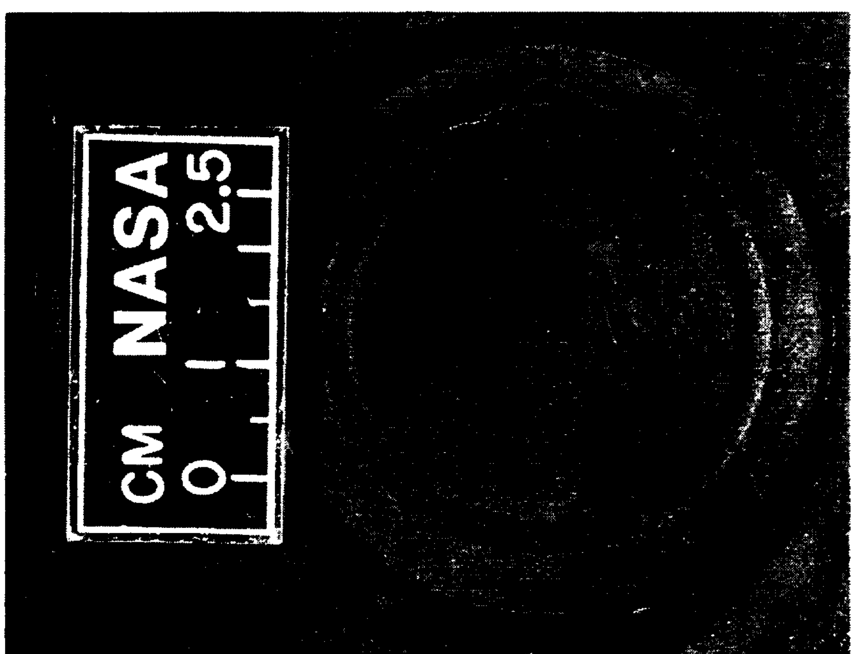


Fig. 6. Strain-age Cracking in a Welded and Aged 10.2 cm Diameter Specimen

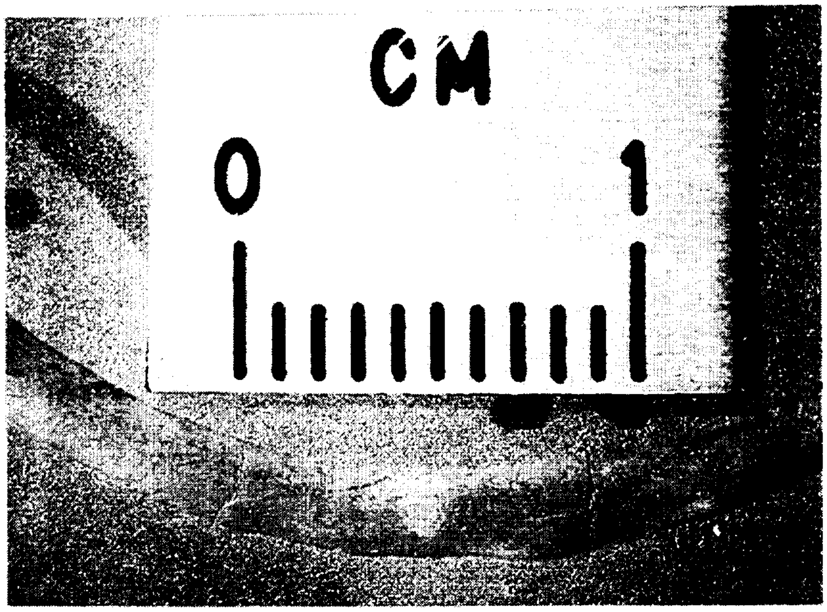


Fig. 7. Strain-age Cracking in a Welded and Solution Treated 10.2 cm Diameter Specimen.

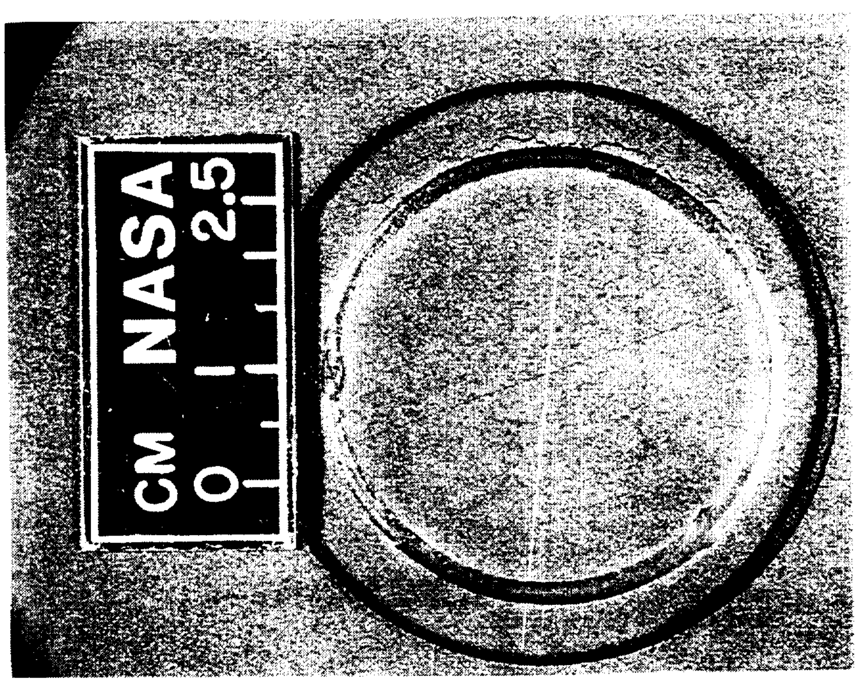


Fig. 8. Cracking in a Simulated Repair Weld - 10.2 cm Diameter Specimen

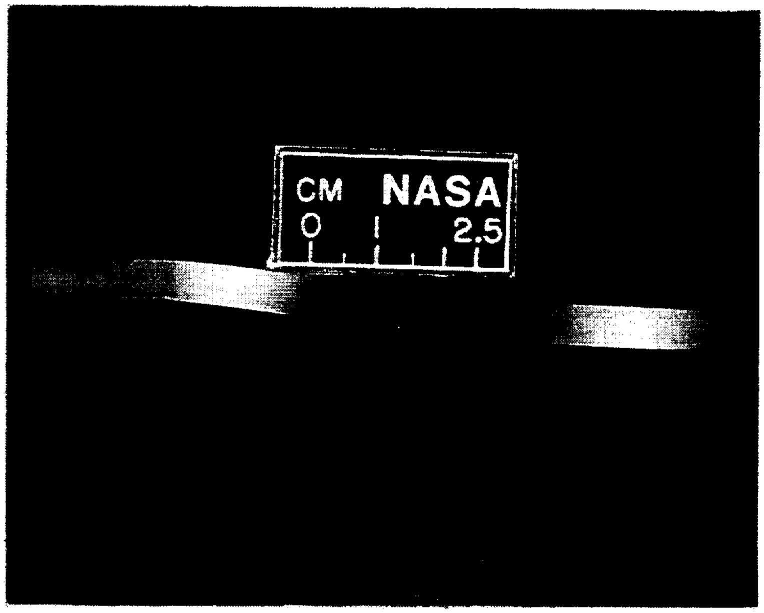


Fig. 9. Severe Warping in 16.5 cm Diameter Specimen.

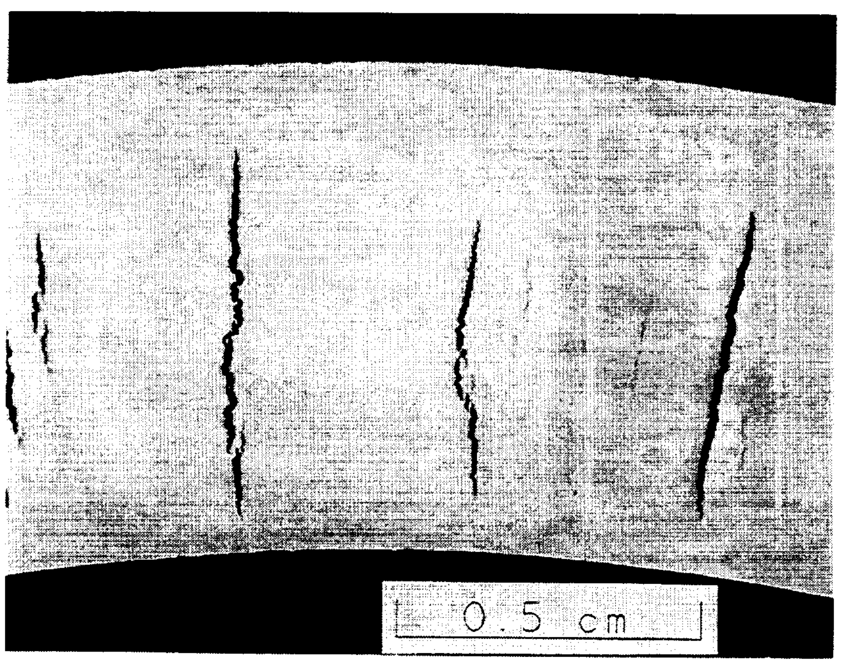


Fig. 10. Sub-surface Cracking in Contractor-welded Pipe - Sectioned Longitudinally Along the Weld Centerline

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